IV. THERMIONIC PLASMAS

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All thermionic energy converters[1] depend on the fact that when a metal is heated it emits electrons, a phenomenon in many ways analogous to the liberation of steam particles when water is heated. This basic property of materials was first noted by Thomas Edison in 1883. The proposal to harness this property to achieve direct energy conversion is credited to Schlichter in 1915. Work on actual devices is considerably more recent, being first reported by Hatsopolous in 1956 and Wilson in 1957, although a thorough examination of the thermionic emission of electrons from the combination of materials most often used today, namely, cesium coated tungsten, was conducted by Langmuir in the 1920's.

The current interest in thermionic research is heavily influenced by a desire to take full advantage of the high temperatures available from nuclear reactors, particularly in the space environment. Since thermionic converters might well operate with a heat rejection of approximately 10^3 K, and since heat rejection itself varies as T^4, thermionic systems should allow for a major reduction in radiator size and hence in specific weight when compared to other lower temperature systems. In common with other direct conversion devices, the thermionic converter has no moving parts. However, it is very distinct from other systems in that it has a high power density, with values of the order of 10 watts per square centimeter currently attainable. The most probable space applications of thermionic conversion systems include power generation for long trips and/or large payloads.

The simplest version of the thermionic converter, namely, the vacuum diode, is shown in figure IV-1(a). The vacuum diode consists of two electrodes, an emitter and a collector, encased in a container which maintains the vacuum and a source of heat to drive the electrons.

Insight into the principles of operation of the vacuum converter can be obtained by looking at figure IV-1(b), which shows a typical interelectrode potential profile for the vacuum converter. On the left is the emitter, with the zero of energy chosen at its Fermi level. The collector with its Fermi level is on the right. Phi is used to indicate the work function. Lower case φ is the vacuum work function, that is,

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[1]The introductory portion of this report follows to a considerable extent the approaches used in refs. 1 and 2.

the amount of energy measured from the Fermi level that an electron needs to escape to vacuum from the interior of a solid. The subscripts e and c stand for emitter and collector, respectively. To trace the path of an electron through one energy conversion cycle, start with an electron that is initially near the emitter Fermi level. If it receives an energy greater than φ_e, it can leave the emitter, where it immediately encounters another barrier, $\Delta\varphi_e$, the space charge barrier resulting from the electrons which preceded it. If the electron initially received an energy greater than $\Phi_e = \varphi_e + \Delta\varphi_e$, it will climb the barrier and move across the interelectrode space to reach the collector. Here it gives up φ_c as heat in moving down to the collector Fermi level. However, a net potential difference v remains between the Fermi levels of the two electrodes, so that, if the emitter and the collector are connected, the electron continues on through the external load performing work on its way.

The following table illustrates some of the physical constraints (ref. 1). For heat-resistant transition metals φ is typically 4 to 5 volts. With a judicious

Metal	Work function
Molybdenum	4.20
Nickel	4.61
Platinum	5.32
Tantalum	4.19
Tungsten	4.52
Cesium	1.89
Tungsten-cesium	1.5
Tungsten-barium	1.6
Tungsten-thorium	2.7

choice of materials, such as an emitter with $\varphi \sim 5.3$ volts and a collector with $\varphi \sim 4.2$ volts, and optimizing the external load losses, one might be able to get an output voltage v of the order of 1 volt. Thus, in order to obtain power output, which is the product of the current I and the output voltage v, of 10 watts per square centimeter, we need current of approximately 10 amperes per square centimeter. However, as indicated in equation (1), the emission current I depends strongly on Φ_e:

$$I = AT_e^2 e^{-\left(e\Phi_e/kT_e\right)} \tag{1}$$

The crucial feature here is that I decreases exponentially as Φ_e increases. In practice, adequate current densities are unattainable in vacuum diodes because the space charge $\Delta\varphi_e$ and hence Φ_e are too large. One might hope to minimize the damaging effects of space charge buildup by going to lower temperatures, using lower work function materials and/or reducing the interelectrode spacing. However, even these approaches require uniform interelectrode spacing of a fraction of a mil to be maintained over a very large temperature range and have so far presented difficult design and stability problems, although new approaches in this direction are currently contemplated.

The most direct, and for some time now the most promising, approach has been the introduction of a sufficiently dense gas of positive ions to neutralize the electrostatic field of the electrons. Primary attention has focused, therefore, on the plasma converter. Cesium is the most commonly used gas because of its low ionization potential. As shown in figure IV-2(a), the cesium converter is a modified vacuum converter which allows for the addition of cesium vapor to the interelectrode region. The density of the vapor is determined by the temperature of the cesium reservoir. The cesium enters the interelectrode region as a gas of neutral atoms and is subsequently ionized by either surface ionization at the hot emitter (unignited mode) or volume ionization in the interelectrode region (ignited mode).

The consequences of introducing cesium can be seen in figure IV-2(b). The primary benefit derived from a cesium plasma is the neutralization of the space charge, that is, reduction of $\Delta\varphi_e$. Another nontrivial benefit, however, is that some of the cesium atoms absorb on the collector, which is relatively cool, while those that come in contact with the emitter, which is hot, will boil off. As shown in the table of work functions, this will lower the collector work function close to that of cesium with the beneficial consequence of increased output voltage.

For a number of reasons including reliability, ease of acquisition, and direct usefulness to development engineers, the principal analytic tool for thermionic converters is the plot of current against voltage, or I-v curve. Figure IV-3 shows one such plot; actually it is a composite of various I-v curves presented slightly out of proportion in order to indicate all the features of interest more clearly.

The major feature is the existence of two modes of operation. These correspond to the two ionizing processes mentioned earlier. The lower portion shows the unignited mode, in which the cesium ions are produced by surface contact ionization. The upper curve shows the ignited mode, in which the ionization takes place in the interelectrode region as a result of electron-atom collisions. Within

these two modes, the major I-v characteristics are further classified by

(1) The deep retarding region which results from the application of a reverse bias voltage to the diode

(2) The apparent saturation region which is a result of either space charge limitation when the electron space charge is incompletely neutralized or the collection of all electrons when there is an adequate (excess) supply of ions

(3) The region of preignition and negative resistance in which a violet-pink glow discharge forms at one point in front of the emitter and eventually covers the entire emitter

(4) That part of the ignited mode, sometimes referred to as the obstructed region, in which there is dark space directly in front of the emitter and an orange flow in the interelectrode region

The second mode appears most promising for power production since the product of I and v is greatest. It has been possible to produce in typical experimental devices current densities of 50 amperes per square centimeter near 0.5 volt for power densities greater than 20 watts per square centimeter.

The paper thus far has dealt with the thermionic conversion process. Now consider the role played by the plasma itself. For perfect neutralization, it is necessary that

$$n_+ = n_- \tag{2}$$

where n is the number density, (+) refers to ions, and (-) refers to electrons. Note that this in no way implies that the current densities are equal. Quite the contrary; the current is given by

$$I_\pm = n_\pm e u_\pm \tag{3}$$

where u is the mean velocity. In thermal equilibrium the kinetic energies are equal:

$$\frac{1}{2} m_+ u_+^2 = \frac{1}{2} m_- u_-^2 \tag{4}$$

so that, for cesium,

$$\frac{I_-}{I_+} = \frac{m_+}{m_-} = 492$$

This leads to the definition of the ion richness parameter β as

$$\beta = 492 \frac{I_+}{I} \tag{5}$$

The converter is electron rich when $\beta \ll 1$, ion rich when $\beta \gg 1$, and approximately neutralized when $\beta \sim 1$.

The second parameter is pd, the product of the pressure and the interelectrode spacing. It is approximately proportional to the number of electron mean free paths in the converter. The effects of β and pd as parameters (ref. 2) are shown in figure IV-4. The major axes define a space in β and pd. Superposed on this is a set of four different I-v curves. Each I-v curve presents the results of operation of the same plane parallel cesium vapor thermionic converter. The striking differences between the four curves arise from the different combinations of β and pd at which each is operated. Curve B is typical of a converter operating at $\beta < 1$ and pd < 10. The curve shows the full range of operation shown in figure IV-3 with the exception that the small current region is considerably contracted. If β is kept the same, but pd (the number of mean free paths) increases, the transition and negative resistance regions disappear and the converter operation goes smoothly from ignited to unignited modes, as shown by curve A. As both β and pd are increased, we would find that the apparent saturation region is completely absent as in curve C.

Figure IV-5 shows a typical set of interelectrode potential diagrams for the ignited mode as measured by Baksht and coworkers and reported in the Journal of Soviet Physics (ref. 3). The emitter is on the left, and the different curves are for the various spacings indicated. The difference between the potential heights at the emitter and collector is the internal plasma loss of the order of 1 volt. Most of this loss represents energy required to maintain the plasma while a lesser source of loss to be considered is back heating of the emitter by the plasma. Considerable effort has been directed toward obtaining a better understanding of these loss processes. At this point we should note that, in addition to the usual difficulties of analysis present in all plasmas, there are further complications unique to thermionic plasmas. These include the active nature of the container walls. That is, the walls emit and collect electrons and ions as an essential part of the device operation. Also, the plasma dimensions are very small, that is,

the space between emitter and collector is usually of the order of 5 to 10 mils.

The Lewis Research Center has carried on a program of theoretical and experimental work designed to enhance our knowledge of thermionic plasma processes and thus ultimately to improve the converter performance. Two theoretical studies of the plasma have been undertaken with emphasis given to the role played by the sheaths or boundary layer between the electrodes and the bulk plasma. In a work by James F. Morris the sheath parameters were coupled to electrodes as well as the plasma in a formulation which allowed for feedback between the components, as opposed to the more primitive theories which replaced the sheaths by passive boundary conditions. In addition to giving new insights into plasma processes under unignited isothermal conditions, it eliminated such inconsistencies of the earlier theories as the existence of a net current at equilibrium (ref. 4). Another theoretical study undertaken by Peter Sockol applied transport theory to the sheath itself in the unignited mode (ref. 5). This study is currently being extended to the ignited mode with emphasis on understanding the mechanism of nonthermal ionization in the immediate vicinity of the emitter. The matter of heat loss to the emitter from the plasma has been analyzed by Roland Breitwieser, who developed a technique based on application of quite general thermodynamic constraints to the analysis of I-v curves (ref. 6).

An experimental program to evaluate a possible new technique for reducing the losses incurred in maintaining the plasma was initiated a few years ago by Ralph Forman. His work involved the investigation of the enhanced electrical properties of a converter when placed in the radiation field of a nuclear reactor (ref. 7). Figure IV-6 depicts the envisioned process. It was anticipated that the γ-rays present in a reactor would as a result of interaction with the converter electrodes cause the generation of large numbers of relatively low energy electrons. These secondary electrons would, upon collision with the gas atoms present in the interelectrode space, excite (and possibly ionize some) neutral atoms. These atoms being in excited states rather than in the ground state would be more easily ionized to produce ignition. Preliminary in-pile investigations have exhibited some of the anticipated features, as shown in figure IV-6. These data are for a cylindrical thoriated tungsten emitter operating in a xenon environment. In the absence of γ radiation the current is negligible at low voltages, and ignition occurs near 8 volts, which is approximately the energy of the first excited state for xenon. When the same convertor is operated in a reactor, two changes occur. First, there is an enhancement of the low voltage output believed to result from the ionization by secondary electrons, and second, there is a drop in the voltage necessary to cause ignition believed to result from the higher density of excited states. These changes become

more pronounced as the γ radiation flux increases. It is anticipated by analogy with the β-pd plots of figure IV-4 that, with a judicious choice of operating conditions (e.g., the gas and its pressure, electrode materials, interelectrode spacing), it should be possible to cause further enhancement and obtain ignition at much lower voltage. If this hoped for behavior should materialize, there are two possible applications. One, there is the possibility of sufficient enhancement to generate useful power in the unignited mode. Two, there is the possibility that in the ignited mode cesium could be replaced by an inert gas. Cesium initially found favor because of its low ionization potential, but the γ-rays would in effect give inert gases effective ionization potentials that are nearly that of cesium. This substitution of inert gas for cesium would eliminate many of the materials compatibility difficulties arising from the highly corrosive nature of cesium. In spite of the favorable preliminary results obtained thus far, this program, by virtue of being an in-reactor study, is very difficult to perform and expensive to maintain. However, since the reactor generated γ-rays do not interact directly with the neutral gas atoms but rather serve only to generate secondary electrons, it was suggested that for test purposes it might be possible to generate secondary electrons from a source other than a reactor. This was investigated theoretically and indeed found to be feasible. Figure IV-7 shows a schematic drawing of the experimental reactor simulation setup that is being operated by Robert Bacigalupi using the Lewis Research Center Dynamitron (ref. 8). The electron beam incident from the left is generated in the Dynamitron, passes through the thin collector, and strikes the emitter causing both electrodes to emit secondary electrons. It has proved possible using the Dynamitron and a converter similar to the one used by Forman to generate secondary electron fluxes similar to those present in the reactor environment, and thus to reproduce out of core the I-v curves previously obtained in the reactor. Work is presently under way to extend the operating range of this setup. As a further check on the accuracy of this analysis, namely, that the enhanced operation does come from the interaction of secondary electrons with the plasma, and also as a more versatile technique for determining the effects of using different gases and electrodes, a separate microwave diagnostic experiment is currently being initiated by James Dayton. In this, the arrangement is similar to the converter experiment in the Dynamitron except that the diode is replaced by a simple container of gas. The plasma is irradiated by a microwave signal of variable frequency, and the reflected signal is compared with the incident signal. The type of information generated this way is shown in figure IV-8. When the beam of the Dynamitron is off, the reflected signal is as shown by curve A, there being a sharp resonant absorption by the plasma at a characteristic frequency. When the beam is turned on, the microwave signal is reflected as in curve B. The frequency shift can

be related to the charge density while the resonance broadening is related to collision frequency ν, as shown in the following equations:

$$\frac{\Delta f}{f_0} \cong \frac{1}{2}\frac{n}{n_c} \tag{6}$$

$$\frac{\delta f_1}{f_1} - \frac{\delta f_0}{f_0} \cong \frac{\Delta f_0 \nu}{\pi f_0^2} \tag{7}$$

It is anticipated that this dual program will permit rather rapid investigation of a large number of electrode materials and plasma combinations. Of particular interest are the effect that the introduction of a Penning mixture[2] might have on plasma densities and the effect that the secondary electrons might have on recombination rates. While this latter research activity is still in its early phase, it already promises to yield much information of value to an overall understanding of plasma phenomena in the thermionic energy conversion process.

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[2] A Penning mixture is a combination of two gases such that one species has a metastable state (e.g., neon at 16.6 V) slightly above the ionization potential of the other species (e.g., argon at 15.7 V). In such instances the ionization process can be quite efficient.

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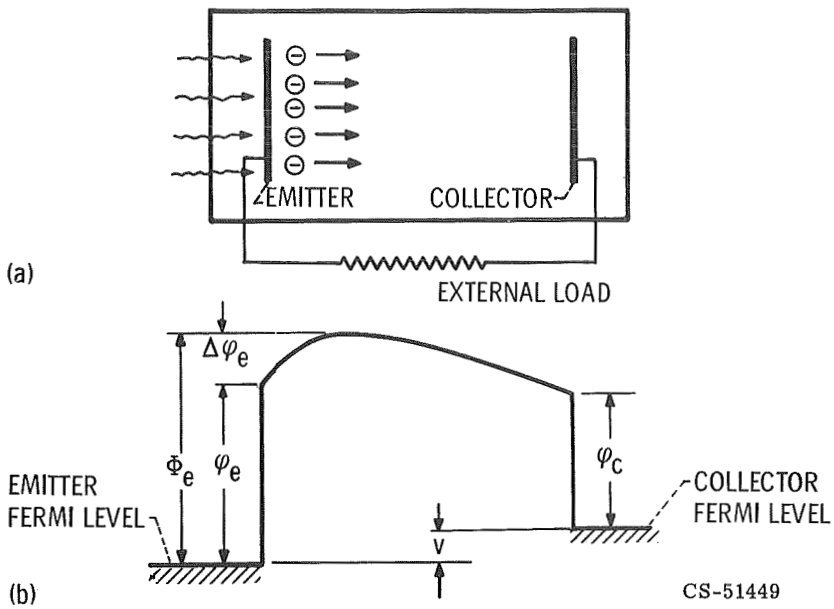
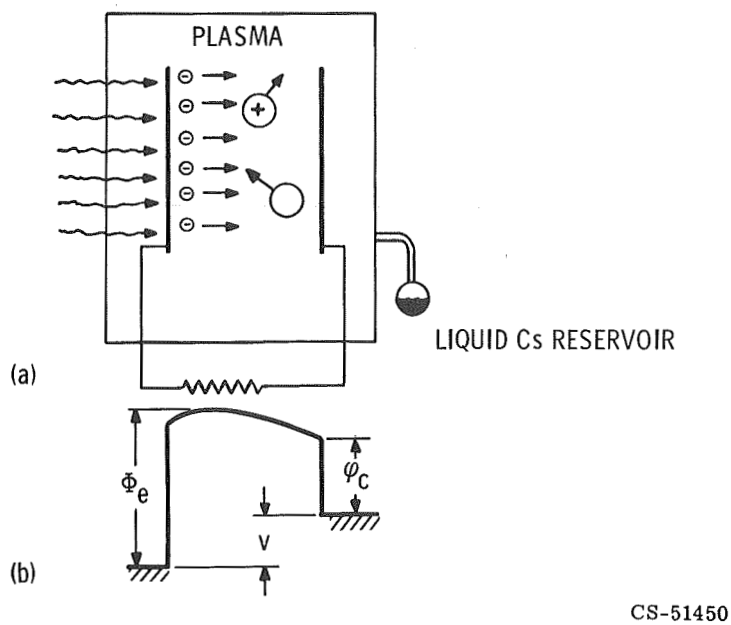


(a) Schematic diagram of thermionic converter.
(b) Interelectrode potential diagram.

Figure IV-1. - Vacuum thermionic energy converter.



(a) Schematic diagram of thermionic converter.
(b) Interelectrode potential diagram.

Figure IV-2. - Plasma (cesium) thermionic energy converter.

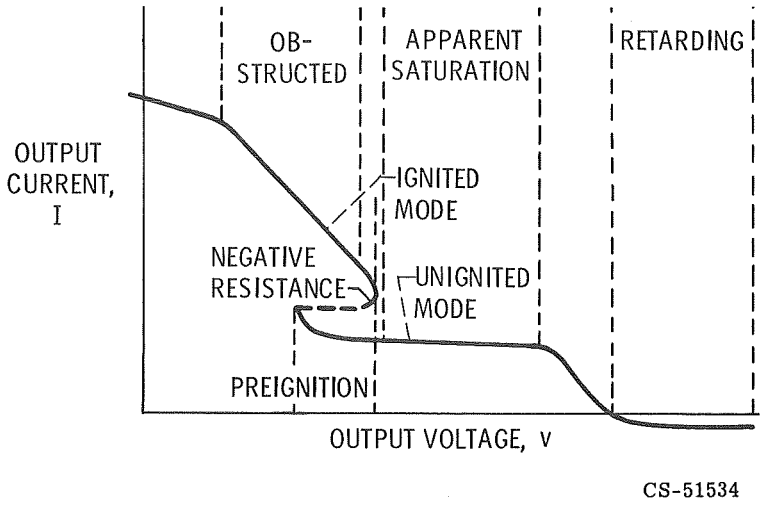


Figure IV-3. - Typical current-voltage characteristic for plasma thermionic energy converter (ref. 1).

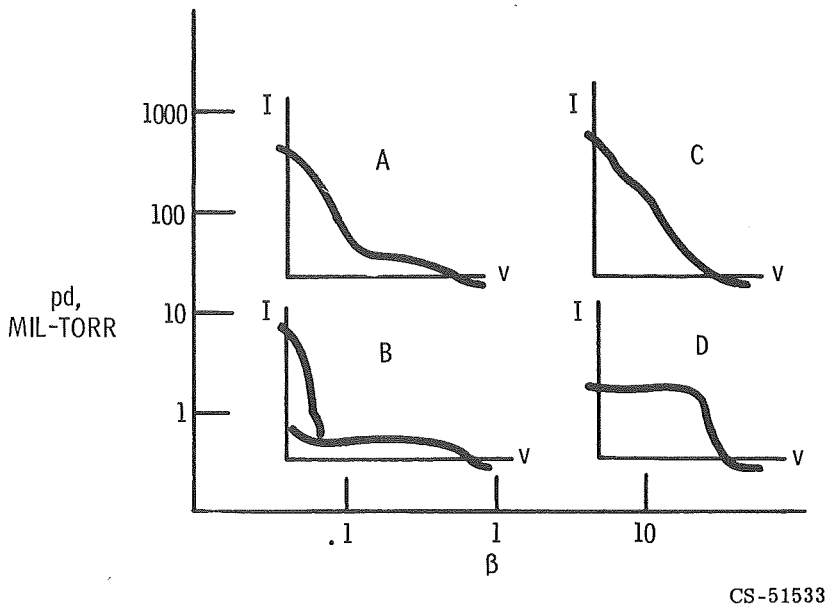


Figure IV-4. - Set of four current-voltage characteristics reflecting dependence of converter performance on ion richness parameter β and pressure-spacing parameter pd (ref. 2).

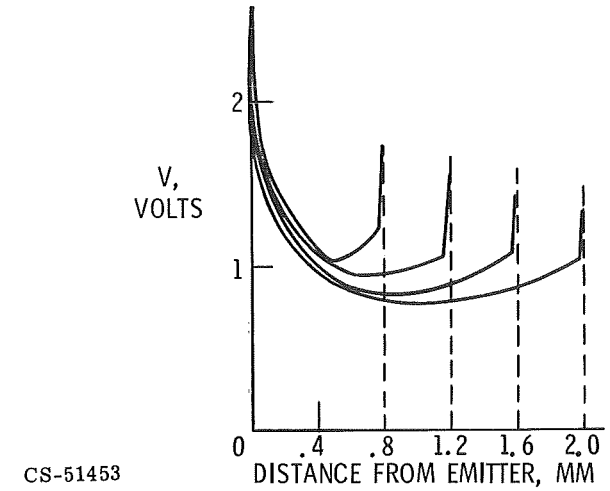


Figure IV-5. - Effect of electrode spacing on interelectrode potential. Cesium pressure, 1.0 millimeter of mercury; emitter temperature, 1680 K; current density, 1.7 amperes per square centimeter (ref. 3).

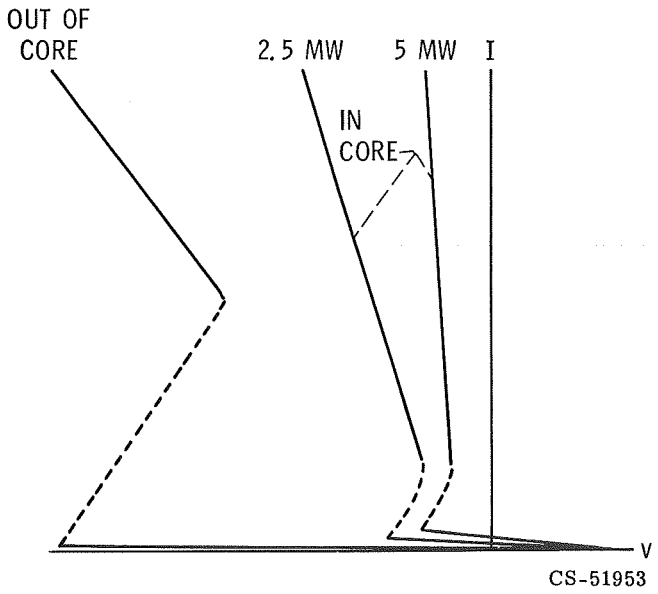


Figure IV-6. - Typical results for cylindrical converter operated in xenon environment. Power units (MW) correspond to power level of reactor employed (Sterling Forest) with 2.5 megawatts approximately equivalent to 0.75 watt per gram.

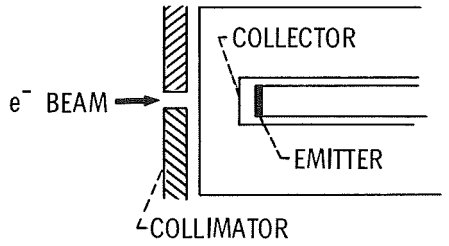


Figure IV-7. - Dynamitron simulation. Emitter, 2 percent thorium-tungsten; gas, xenon at 55 torr; spacing, 1 millimeter.

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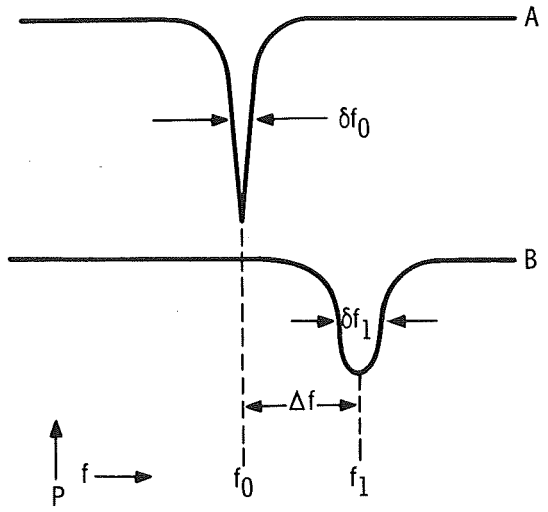

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Figure IV-8. - Reflected signal obtained from microwave plasma analysis with electron beam off (curve A) and with electron beam on (curve B).